AN EXPERIMENTAL STUDY OF THE FLOW OF WATER THROUGH COARSE GRANULAR MEDIA

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1. Introduction

The velocity-hydraulic gradient relationship for the flow of fluids through porous media has long been the subject of discussion. The appearance of a number of papers [1 to 7] on this subject in recent years has indicated that no general agreement has yet been reached as to its form.

The practical difficulties of covering an extensive range of flow conditions for particular porous media and the frequently large scatter of experimental results seem to have been the main reasons for the appearance of a number of conflicting equations for this relationship.

For low flow rates, Darcy's law has been almost universally accepted. This law may be written in the form

$$S = aV$$

with S : hydraulic gradient;

a : constant = reciprocal of coefficient of permeability, k ;

V : « flow » velocity = Q/A ;

Q : discharge;

A : gross cross-sectional area normal to the flow.

There has, however, been a wide range of values of Reynolds number reported for the upper limit of validity of the law. Scheidegger [8] quotes values ranging from 0.1 to 75.

For high flow rates formulae such as the following have been proposed :

(i) $S_p = aV + bV^2$ [Forchheimer, 9]
later modified to:

$$S_p = aV + bV^2 + cV^3;$$

to agree better with experimental results:

$$S_p = \text{pressure gradient} = \gamma S;$$

$$\gamma = \text{specific weight of fluid};$$

a, b, c , are constants.

(ii) $S = aV^n$ (Escande [10]; Wilkins [12]);
(Slepička [3]; Parkin [11]);
(Anandakrishnan and Varadarajulu [1]);

with a, n constants.

(iii) friction factor-Reynolds number correlations such as :

$$f_p = \frac{24.2}{\mathcal{R}_p^{0.2}} \text{ (Bakhmeteff and Feodoroff [13])}$$

with f_p = friction factor in the equation:

$$S = \frac{f_p V^2}{2gd} P^{-5/3}$$

and $\mathcal{R}_p : (Vd/\nu) P^{-1/2}$;

P : porosity;

d : particle diameter;

g : acceleration due to gravity;

ν : kinematic viscosity.

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▲
Photo 1/ General view of permeameter.
Vue d'ensemble du perméamètre.

▲
Fig. 1/ Diagram of permeameter and outlets.
Schéma du perméamètre, avec ses conduites d'écoulement.

For a particular porous medium and fluid, this equation reduces to an exponential equation of type (ii) with $n = 1.8$.

The deviation from Darcy's law at high flow rates has been attributed both to inertial effects and the onset of turbulence. Current opinion seems to be that the deviation is initially caused by gradually increasing inertial effects and that at some later stage the onset of turbulence occurs. Experimental evidence on the dispersion of dye streams published by Schneebeli [14] supports this view.

At very low rates of flow water, the validity of Darcy's law has been questioned for fine-grained porous media, particularly clays. Deviations have been attributed to "electro-chemical" surface effects between the fluid and the solid particles ([2], [3], [4]).

The tests on the flow of water through coarse granular media reported in this paper were intended to cover as great a range of flow conditions as possible. It was hoped that by extending the range of results for particular media the form of the velocity-hydraulic gradient relationship for the flow of water might be made more clear.

2. Experimental apparatus

The permeameter shown in diagrammatic form in Figure 1 was designed to enable permeability tests to be carried out on coarse granular media over a wide range of flow rates and hydraulic gradients.

Special features were

- (i) the method used to eliminate the flow through the zone near the wall;
- (ii) the provision of a range of outlets to allow large and small flow rates to be measured accurately;
- (iii) the introduction of a piezo-electric probe to detect the onset of turbulence in the flow.

The downward flow type was adopted because of the complexity of the outlet arrangements. Having the simpler inlet section at the top allowed the permeameter to be dismantled easily for filling. No problem was anticipated with entrapped air as only coarse materials were to be tested.

Photo 4 ►
Pressure equality
indicator.
*Indicateur d'égalité
des charges.*

◀ **Photo 2**
Outlet section of
permeameter showing
inner tube.
*Section d'écoulement
du perméamètre,
avec son tube
intérieur.*

Photo 5 ►
Arrangement
of manometers.
*Disposition
des manomètres.*

◀ **Photo 3**
Material supporting
grids in
permeameter.
*Grilles-supports des
matériaux, à
l'intérieur du
perméamètre.*

The test section was 4 feet in length and 22½ inches in diameter. It was preceded by a 3 feet long baffled inlet section and followed by a 3 feet long outlet section.

The outlet section was provided with a 14 inch diameter inner tube designed to allow the flow down a central core of the material under test to be excluded from and measured separately from the flow between this core and the permeameter's outer wall. Heavy steel grids overlain by perforated metal sheet and, when necessary, wire gauze were used to support the samples.

A pressure difference indicating device was connected to tapings in the inner and outer walls of the outlet section below the grids. This device consisted of a short length of clear plastic tubing with a smaller diameter clear plastic tube constriction at its mid point. A hypodermic needle was inserted into the constriction to allow dye to be injected.

Four 4-inch diameter outlets spaced symmetrically around the outlet section allowed water entering its outer portion to be led into a collecting box and thence to the measuring tanks.

The flow from the inner section was led direct to the measuring tanks via a central 6-inch diameter outlet.

Piezometer tapings were spaced around the test section at a number of levels to allow head losses to be measured. Plastic tubes of equal lengths were led from the four tapings at each level to junction boxes from which single tubes were taken to manometers.

Head losses were measured over a 2 feet length except for the coarsest materials for which a 3 feet length was used. Entry and exit zones 6 inches deep were maintained above and below these lengths.

Three manometers were needed to cover the range of hydraulic gradients with the required accuracy. A mercury-water U-tube was used to measure head losses from 25 to 10 feet of water, a water U-tube for differences from 10 feet to 0.5 foot and a pair of Casella micromanometers connected as an inverted water-air U-tube for differences from 15 centimetres to 0.1 centimetre.

Photographs 1 to 5 show a general view of the permeameter and a number of details.

Fig. 2

Sieve analysis of river gravels.

Courbes granulométriques des graviers de rivière.

Photo 6

Photo 7

Fig. 3

Sieve analysis of crushed blue metal.

Courbes granulométriques de la dolérite broyée.

3. Experimental procedure

A series of permeability tests was performed on samples of approximately 8 or 12 cubic feet of a number of granular materials.

Each material was loaded into the permeameter by pouring it uniformly over the cross-section from a height of 4 feet. No form of compaction was attempted. When the test section was filled to the required height the surface was levelled and its height measured. It was then covered with a perforated metal grid to prevent displacement of the surface particles. The surface level was checked again after the completion of tests.

As a pre-test routine, water was run through the permeameter at the maximum flow rate to allow the material to settle and to wash out any loose fines. The flow was maintained until the head loss over the test length became constant.

After the sample had stabilised, corresponding flow rates and head losses were measured over a range of hydraulic gradients from 10 to 10^{-4} .

For each test, the pressures in the inner and outer

portions of the outlet section were equalised by adjusting the outlet valves until dye injected in the indicator remained stationary. This procedure was intended to maintain a constant piezometric head across the base of the sample so that the distribution of flow through the test section would be unaffected by the presence of the inner outlettube.

Flow rates were measured by weighing or measuring the volume of water discharged during a measured time interval. Velocities of flow through the inner core and the total cross-section of the permeameter were calculated by dividing these flow rates by the appropriate cross-sectional areas.

Hydraulic gradients were calculated by dividing measured head losses by the vertical distance between piezometer tappings.

Porosities were determined by calculation from the weights of the samples, specific gravities and the gross volumes occupied in the permeameter at the end of the tests. The results were checked by measuring volumes of water drained from the test section between the piezometer levels and making allowance for the water retained on the particles.

Photos 6 to 18 :MATERIALS USED
IN PERMEABILITY TESTS**Photos 6 à 18 :**MATÉRIAUX EMPLOYÉS DANS
LES ESSAIS DE PERMÉABILITÉ**Photo**

- 6/ BM4. 3 inch blue metal.
BM4. Dolérite de 76 mm.
- 7/ G6. 3 inch river gravel.
G6. Gravier de rivière de 76 mm.
- 8/ G7. 6 inch river gravel.
G7. Gravier de rivière de 152 mm.
- 9/ G4. 3/4 inch river gravel.
G4. Gravier de rivière de 19 mm.
- 10/ G5. 1 1/2 inch river gravel.
G5. Gravier de rivière de 38 mm.
- 11/ BM3-2. 3/4 inch blue metal.
BM3-2. Dolérite de 19 mm.
- 12/ BM3-1. 3/4 inch blue metal.
BM3-1. Dolérite de 19 mm.
- 13/ BM4. 1 1/2 inch blue metal.
BM4. Dolérite de 38 mm.
- 14/ G1. Nepean river sand.
G1. Sable de rivière.
- 15/ G2. 1/4 inch river gravel.
G2. Gravier de rivière de 6,3 mm.
- 16/ G3. 3/8 inch river gravel.
G3. Gravier de rivière de 9,5 mm.
- 17/ BM1. 3/16 inch blue metal.
BM1. Dolérite de 4,7 mm.
- 18/ BM2. 3/8 inch blue metal.
BM2. Dolérite de 9,5 mm.

Photo 8 **Photo 11** **Photo 12****Photo 15** **Photo 9** **Photo 13****Photo 17** **Photo 10** **Photo 14****Photo 18** **4. Material tested**

River gravels, crushed rock particles and glass marbles were used for the permeability tests.

The river gravels were composed of particles of hard igneous and metamorphic rocks and minerals derived from these. The coarse and medium gravels consisted entirely of well rounded fragments of quartzite and intermediate igneous rocks. Although rounded, many of the particles were somewhat flat. The fine gravels consisted of small semi-angular rock particles and separate mineral grains. Quartz was the predominant separate mineral present with some feldspar. The proportion of quartz increased until for the sand sample it was approximately 98 pc. The angularity of the particles increased with increasing fineness but the tendency towards flatness decreased.

The crushed rock, blue metal, was a crushed dolerite, with angular particles. The smaller sizes had a higher proportion of the lighter minerals as these crush more easily. Of the two samples of

3/4 inch blue metal, sample BM3-2, used in test series No. 1, was more flaky than sample BM3-1.

Sieve analyses of the materials were carried out according to A.S.T.M. Tentative Standard D 422-54 T. The samples used for these analyses were taken from the permeameter after the completion of tests. Results are shown in Figures 2 and 3.

Photographs 6 to 18 illustrate the river gravel and crushed dolerite materials used.

The glass marbles, nominally 16, 25 and 29 mm in diameter, had actual mean diameters of 16.0, 24.9 and 29.0 mm. Standard deviations were 0.3, 0.3 and 0.4 mm respectively. The marble mixture, M 123, consisted of these marbles in the proportions 1.23 : 1.05 : 1.00 by weight. The marbles were only slightly eccentric in shape and, since regular packings were not attempted, they were treated as spherical particles.

The water supply was taken from a reservoir with a predominantly sandstone catchment. The mineral content of the water was low. Because only coarse grained materials were being tested, no attempt was made to remove dissolved gases from the water.

◀ Fig. 4

Permeability tests on crushed blue metal.

Essais de perméabilité avec de la dolérite broyée.

NOTE: Heavy lines for flow through inner section of permeameter.
Light lines for flow through total cross section of permeameter.

NOTA: Les traits épais désignent l'écoulement par la section intérieure du perméamètre.
Les traits minces désignent l'écoulement par la section globale.

5. Results

The results of the permeability tests are plotted in Figures 4 to 8. They indicate that, for the coarse granular media tested and hydraulic gradients between 10^{-4} and 10, the velocity-hydraulic gradient relationship is a discontinuous exponential one of the form.

$$S = aV^n$$

In all cases, a number of flow regimes which plot as straight lines on the log plots are apparent. This is true for both the flow through the inner section and the flow through the total cross-section of the permeameter. Table 1 gives a summary of the values of velocity and hydraulic gradient for the limits of experimental data and the intersection points of the straight line sections of the graphs, together with calculated values of a and n . In accordance with Slepíčka's [3] notation, regime for which n equals 1 have been called linear regimes, those for which n is less than 1 have been called

pre-linear regimes and those for which n is greater than 1 have been called post-linear regimes.

Linear regimes.

Linear regimes are apparent for the 3/16 inch and 3/8 inch blue metal,—the 1/4 inch and 3/8 inch gravel and sand, 16 mm marbles and the mixture of 16, 25 and 29 mm marbles. The apparatus available for head loss measurements precluded the possibility of detecting linear regimes for the coarser materials as sufficiently low hydraulic gradients could not be measured.

Within the limits of accuracy of the experimental results, values listed in Table 1 for n for the linear regimes do not differ significantly from 1.00.

It should be noted that the linear regime is the only one for which the exponent, n , is sensibly constant despite changes in porosity and particle shape, size and grading.

Post-linear regimes.

The plots for each test series which covered an appreciable range of flows above the upper limit of

◀ Fig. 5

Permeability tests on river gravels.

Essais de perméabilité avec des graviers de rivière.

NOTE: Heavy lines for flow through inner section of permeameter.
Light lines for flow through total cross section of permeameter.

NOTA: Les traits épais désignent l'écoulement par la section intérieure du perméamètre.
Les traits minces désignent l'écoulement par la section globale.

the linear regime reveal the existence of a number of post-linear regimes, each with an exponent, n , between 1 and 2. The maximum values of n for each of the coarser media lie between 1.8 and 1.9.

Pre-linear regimes.

The results for 3/16 inch and 3/8 inch blue metal, sand(and - 1/4 inch river gravel appear to indicate the existence of a lower limit to the linear regime and the occurrence of an adjacent pre-linear regime. For the low hydraulic gradients involved, the scatter of the plotted points is greater than for higher hydraulic gradients but there appears to be sufficient evidence to postulate a departure from Darcy's law in the cases mentioned. The results for 3/16 inch blue metal, in particular, for which very stable atmospheric conditions allowed small head loss measurements to be made more accurately, plot closely on the pre-linear line.

Note that in fitting the pre-linear lines to the experimental points, more weight has been placed on those at higher hydraulic gradients.

Turbulence detector results.

The velocities at which random pressure fluctuations were registered by the piezo-electric detector are marked on the velocity-hydraulic gradient plots. There is no significant correlation between the median grain sizes of the media and the velocities at which the fluctuations were found to commence. Reynolds numbers corresponding to the indicated velocities range from approximately 1 to 150.

Since the velocities determined vary from $7 \cdot 10^{-4}$ ft/sec to $7 \cdot 10^{-3}$ /sec they do not correspond to any particular flow rate or approach velocity in the inlet section of the permeameter. It is, therefore, unlikely that the response of the indicator was connected with the onset of turbulent conditions in the inlet section and associated vibration of the permeameter.

The results do appear to give a general indication of the commencement of turbulence at the location of the probe tapping. However, further development of the method is needed to obtain the average of conditions at a number of points throughout the flow.

Summary of data defining flow regi

TEST ESSAI	MATERIAL Matériau	PORO- SITY Porosité P (pc)	POST-LINEAR REGIME Régime post-linéaire											
			V (ft/sec)	S	α	n	V (ft/sec)	S	α	n	V (ft/sec)	S	α	
1	BM3 2.3/4" Blue Metal <i>Dolérîte</i>	45.5	*0.805	*10.0	15.0	1.87	9.8×10^{-2}	0.194	12.7	1.73	3.31×10^{-2}	2.96×10^{-2}	6.25	1
2	M1 23 Marble Mixture <i>Billes mélangées</i>	37.9	*1.25	*11.5	7.51	1.87	0.138	0.188	6.16	1.76				
4	G1 Nepean Sand <i>Sable</i>	38.7												
5	G3 3/8" River Gravel <i>Grav. de rivière</i>	39.2					*0.209	*10.0	1.47	1.72	4.35×10^{-2}	0.675	71.8	1
6	G2 1/4" River Gravel <i>Grav. de rivière</i>	41.8					*0.200	*13.4	210	1.71	0.141	7.37	128	1
8	BM1 3/16" Blue Metal <i>Dolérîte</i>	47.7					*0.350	*12.7	76.7	1.71				
9	BM2 3/8" Blue Metal <i>Dolérîte</i>	45.8					*0.463	*12.5	47.6	1.74				
10	G6 3" River Gravel <i>Grav. de rivière</i>	36.9	*1.02	*5.04	4.85	1.86	3.27×10^{-2}	8.0×10^{-3}	2.62	1.69				
11	BM5 3" Blue Metal <i>Dolérîte</i>	48.3	*0.94	*10.0	11.3	1.88	3.59×10^{-2}	2.00×10^{-2}	7.89	1.80				
12	G5 1.1/2" River Gravel <i>Grav. de rivière</i>	37.2	*0.855	*10.0	13.4	1.85	5.90×10^{-2}	7.17×10^{-2}	7.97	1.67				
13	G4 3/4" River Gravel <i>Grav. de rivière</i>	36.7	*0.63	*10.0	25.4	1.83	4.6×10^{-2}	9.0×10^{-2}	11.9	1.59	1.36×10^{-2}	1.30×10^{-2}	7.20	1
14	BM4 1.1/2" Blue Metal <i>Dolérîte</i>	43.8	*0.95	*10.0	11.0	1.89	7.1×10^{-2}	7.5×10^{-2}	7.60	1.75				
15	BM3 1.3/4" Blue Metal <i>Dolérîte</i>	42.8	*0.69	*10.0	19.7	1.82					4.10×10^{-2}	5.85×10^{-2}	6.66	1
16	M1 16 mm Marbles <i>Billes</i>	36.9	*0.895	*8.0	9.80	1.83	9.4×10^{-2}	0.131	6.91	1.68				
17	M2 25 mm Marbles <i>Billes</i>	36.9	*1.06	*7.00	6.28	1.87	0.180	0.255	5.40	1.78				
18	G7 6" River Gravel <i>Grav. de rivière</i>	40.6	*1.35	*2.50	1.41	1.91	7.0×10^{-2}	8.8×10^{-3}	1.07	1.80				
19	M1 16 mm Marbles <i>Billes</i>	41.5	*0.510	*1.60	5.55	1.85	0.172	0.215	4.52	1.73				
20	M1 16 mm Marbles <i>Billes</i>	37.2	*0.450	*1.88	7.98	1.81	9.1×10^{-2}	0.104	6.29	1.71				
21	BM3 1.3/4" Blue Metal <i>Dolérîte</i>	51.5	*0.400	*1.50	8.45	1.89	8.0×10^{-2}	7.2×10^{-2}	5.33	1.70	2.33×10^{-2}	8.8×10^{-3}	2.05	1.
22	M3 29 mm Marbles <i>Billes</i>	38.5	*1.13	*6.00	4.79	1.85	5.80×10^{-2}	2.45×10^{-2}	2.30	1.60				

bleau I

sumé des données définissant les régimes d'écoulement

POST-LINEAR REGIME Régime post-linéaire					LINEAR REGIME Régime linéaire				PRE-LINEAR REGIME Régime pré-linéaire					TEST ESSAI
V (ft/sec)	S	a	n	V (ft/sec)	S	a	n	V (ft/sec)	S	a	n	V (ft/sec)	S	
12×10^{-2}	5.45×10^{-3}	1.70	1.28	1.8×10^{-3}	5.2×10^{-4}	0.253	0.98	5.4×10^{-4}	1.6×10^{-4}					1
31×10^{-2}	1.00×10^{-2}	3.03	1.57	9.9×10^{-3}	2.19×10^{-3}	0.239	1.02	7.0×10^{-4}	1.48×10^{-4}					2
50×10^{-2}	11.5	442	1.18	1.50×10^{-2}	3.13	211	1.00	6.1×10^{-5}	1.28×10^{-2}	69	0.89	2.0×10^{-6}	6.2×10^{-4}	4
12×10^{-2}	8.95×10^{-2}	23.3	1.24	3.27×10^{-3}	1.95×10^{-2}	6.40	1.01	1.74×10^{-4}	1.00×10^{-3}					5
30×10^{-2}	1.44	60.1	1.21	7.5×10^{-3}	0.160	21.3	1.00	1.30×10^{-4}	2.78×10^{-3}	6.1	0.86	6.0×10^{-6}	1.97×10^{-4}	6
01×10^{-2}	0.179	12.4	1.20	4.6×10^{-3}	1.96×10^{-2}	4.63	1.01	1.54×10^{-3}	6.45×10^{-3}	1.10	0.79	4.5×10^{-5}	3.9×10^{-4}	8
00×10^{-2}	0.170	16.9	1.42	6.70×10^{-3}	1.40×10^{-2}	2.02	0.99	1.04×10^{-3}	2.20×10^{-3}	0.55	0.80	9.0×10^{-5}	3.07×10^{-4}	9
0×10^{-3}	9.0×10^{-4}													10
0×10^{-3}	1.2×10^{-3}	0.92	1.36	1.7×10^{-3}	1.6×10^{-4}									11
0×10^{-3}	1.64×10^{-3}	1.31	1.31	1.4×10^{-3}	2.38×10^{-4}									12
5×10^{-3}	3.30×10^{-3}	2.74	1.29	1.2×10^{-3}	4.83×10^{-4}									13
3×10^{-2}	3.5×10^{-3}	2.27	1.47	5.0×10^{-3}	9.3×10^{-4}									14
0×10^{-3}	2.14×10^{-3}	1.79	1.24	1.2×10^{-3}	4.27×10^{-4}									15
0×10^{-2}	1.72×10^{-2}	2.88	1.43	5.17×10^{-3}	1.53×10^{-3}	0.309	1.01	8.0×10^{-4}	2.33×10^{-4}					16
2×10^{-2}	1.69×10^{-2}	2.70	1.57	1.00×10^{-3}	5.4×10^{-5}									17
5×10^{-3}	1.00×10^{-4}													18
2×10^{-2}	4.00×10^{-3}	1.22	1.41	7.7×10^{-3}	1.29×10^{-3}	0.205	1.04	1.16×10^{-3}	1.8×10^{-4}					19
0×10^{-2}	6.5×10^{-3}	2.00	1.43	6.5×10^{-3}	1.52×10^{-3}									20
0×10^{-3}	1.00×10^{-3}	0.712	1.25	2.00×10^{-3}	3.05×10^{-4}									21
0×10^{-3}	3.30×10^{-4}													22

◀ Fig. 6

Permeability tests on glass marbles.

Essais de perméabilité avec des billes de verre.

NOTE: Heavy lines for flow through inner section of permeameter.
Light lines for flow through total cross section of permeameter.

NOTA: Les traits épais désignent l'écoulement par la section intérieure du perméamètre.
Les traits minces désignent l'écoulement par la section globale.

Permeameter wall effects.

The heavy and light lines in Figures 4 to 6 respectively represent velocity-hydraulic gradient relationships determined for the inner section and total cross-section of the permeameter. Filled in symbols are experimental points plotted for the inner section and open symbols are points plotted for the total cross-section flows. It will be seen that in almost all cases the velocity through the inner section is less than the velocity averaged over the total area. The difference is presumably caused by a disproportionate flow of water passing down the zone immediately adjacent to the wall of the test section. Against this wall no "interlocking" of the particles is possible and voids of a nature different from those present in the material away from the wall must occur.

For the tests on the coarser materials the difference between the two calculated velocities is of the order of 5 to 15 per cent. Since there are no appreciable differences in slope of the corresponding lines on the log-log plots the equation $S = aV^n$ holds for

both velocities with values of n unchanged. The results of the experiments suggest that the values of n determined for coarse granular media in a permeameter in which the whole of the flow is measured should not be in error to any significant extent but that the values of a may be in error by as much as 15 %.

The abrupt change shown on Figure 5 for 3/8 inch river gravel is attributed to the presence of a small flaky particle which was found projecting from one of the pressure equality indicator tappings at the end of tests.

The exceptional results for sand may be due to material having been accidentally reduced to a "quick" condition during an attempt to remove entrapped air. Although the surface of the sample was re-levelled after the incident, the packing was undoubtedly altered.

Test Series 3 and 7 were abandoned because of the loss of material which escaped between the retaining grid and the wall in the absence of a gauze layer. They were repeated as Series 6 and 8.

Fig. 7/ Permeability tests on 3/4-inch blue metal for different porosities.

Essais de perméabilité avec de la dolérite de 19 mm, et pour diverses porosités.

Fig. 8/ Permeability tests on 16-mm glass marbles for different porosities.

Essais de perméabilité avec des billes de verre de 16 mm, pour diverses porosités.

6. Discussion

Wall effects.

A detailed quantitative investigation of wall effects in permeameters was not the purpose of the tests reported. The apparatus was designed to eliminate the effect by allowing measurement of the flow through an inner core of material. The thickness of the annular area of flow eliminated was 5 inches compared with a median diameter of 4.3 inches for the coarsest gravel tested. Velocity traverses by Saunders and Ford [15] across the outlet from a porous bed indicated a uniform velocity except for an annular area about one particle diameter thick inside the walls. In this region velocities were as much as 50 pc. higher. Because of this and the fact that with careful filling of the permeameter the voids should not be affected by the walls for more than this distance it was considered that the measured inner flow velocities would be a good approximation to the velocity of flow through a bed of infinite area.

Further work on wall effects is in progress and will be published at a later date.

Velocity-hydraulic gradient relationship.

The results of the tests reported agree with and extend the results of Slepíčka [3], Anandakrishnan and Varadarajulu [1] and a number of other researchers who have proposed exponential relationships of the form $S = aV^n$. The discontinuities between regimes, which become apparent only when results cover a wide range of hydraulic gradient, are for all practical purposes abrupt. A number of previously published results, including those of Bakhmeteff and Feodoroff [13] are better interpreted in terms of a discontinuous exponential function.

It should be noted that the results of Tests Series 1 were taken over a period of a number of days with increasing and decreasing flows, a range of mean pressures and a 5 °C temperature range. A greater number of tests were included in this series to confirm the nature of the graph.

The reason for the abrupt changes in regime is not apparent. It is possible that they are linked with the occurrence of a number of stable flow patterns around particles of the media with sudden changes from one to another.

The assumption in the past of gradual changes may be attributed to the scatter of experimental

Fig. 9/ Friction factor versus Reynolds number.

Coefficient de frottement en fonction du nombre de Reynolds.

results which frequently occurs, the development of general equations from data for a relatively narrow range of flow conditions and frequently to the plotting together of experimental results in friction factor-Reynolds number form for a number of porous media and drawing a curve of best fit between the scatter of points which results.

The occurrence of pre-linear regimes for relatively coarse grained media is important and requires further confirmation. Pre-linear behaviour has previously been considered important only in connection with fine materials such as clays. If it can occur for a material as coarse as 3/16 inch crushed dolerite it is clearly important in estimating groundwater flows. Further work is in progress to extend results in this range.

The failure of Darcy's law to hold at very low flow rates for fine grained materials has been attributed to « electro-chemical » surface effects at the solid-liquid boundaries. The possibility of these effects being significant in coarse grained materials appears to be slight because of the limited sphere of

influence of the solid boundaries. In clays, the thickness of this zone has been estimated to be of the order of one micron. An alternative explanation which is being investigated is the possibility of water behaving as a non-Newtonian liquid at very low flow rates because of the association of its molecules into a quasi-crystalline or polymer structure.

Friction factor-Reynolds number plot.

Friction factors and Reynolds numbers corresponding to limits of data and intersection points of straight lines on Figures 4 to 8 are listed in Table 2 and plotted in Figure 9. The median diameter has been used to calculate the parameters in the form :

$$f = \frac{2gdS}{V^2} \text{ and } : \mathcal{R} = \frac{Vd}{\nu}$$

where f : friction factor;
and $\mathcal{R}$: Reynolds number.

Fig. 10/ $a_{\text{pre-linear}}$ VERSUS a_{linear} .

Coefficient a en régime pré-linéaire, en fonction du coefficient a en régime linéaire.

By combining the equations :

$$S = aV^n \quad \text{and} \quad S = \frac{fV^2}{2gd}$$

it may be shown that lines which plot straight on the log-log V - S plot will plot as straight lines on the log-log f - $\mathcal{R}$ plot.

Since d occurs to the first power in both f and $\mathcal{R}$ a change in d involves a parallel shift of a particular f - $\mathcal{R}$ line at 45° to each axis.

It is thus obvious from inspection of Figure 9 that no single equation linking f and $\mathcal{R}$ will apply to all lines; nor will the choice of different characteristic lengths draw all the lines together to form a single graph.

The only likely solution to the problem of a generalised f - $\mathcal{R}$ plot is in terms of a set of graphs for each family of geometrically similar porous media. The problem is analogous to that of determining a single f - $\mathcal{R}$ graph for all pipes with an unlimited range of shapes and sizes and roughness shapes, sizes and distributions. Attempts in the past to separate particle shape and porosity in an empirical equation for f have failed to give generality.

In the absence of a generalised f - $\mathcal{R}$ plot, it would appear logical to leave the results of permeability tests in terms of velocity and hydraulic gradient, rather than convert them to Reynolds number

Fig. 11/ Hydraulic gradient for upper limit of linear regime (S_{critical}) versus a_{linear} .

Gradient hydraulique correspondant à la limite supérieure du régime linéaire (S_{critique}), en fonction du coefficient a en régime linéaire.

and friction factor form. In most engineering problems involving water, temperature effects are so insignificant compared with other uncertainties that the introduction of a viscosity term is unwarranted.

Correlations from velocity-hydraulic gradient plots.

Attempts by Slepíčka [3] to generalise velocity-hydraulic gradient graphs by correlating permeability with hydraulic gradients for changes of regime and with constants a and n in the equation $S = aV^n$ yielded poor results. Most of the correlation graphs show a large scatter. Similar correlations were attempted for the results of this investigation.

The following plots yielded no significant correlation:

- (i) a for one regime versus a for adjacent regime;
- (ii) a for regime with n about 1.85 versus a for linear regime;
- (iii) a for post-linear regime adjacent to linear regime versus a for linear regime;
- (iv) n about 1.85 versus a for n about 1.85;
- (v) hydraulic gradient for lower limit of linear regime versus a for linear regime.

Table 2

Limiting Reynolds numbers and friction factors for flow regimes

TEST SERIES Série d'essais n°	MATERIAL Matériau	PORO- SITY Porosité P (pc)	CHARACTERISTIC PARTICLE LENGTHS Longueurs caractéristiques des grains				WATER KINEMATIC VISCOSITY Viscosité ciné- matique de l'eau $\nu \times 10^5$ (ft²/sec)	CRITICAL VALUES FROM EXPERIMENTAL GRAPHS Valeurs critiques tirées des courbes expérimentales		REYNOLDS NUMBER Nombre de Reynolds	FRICTION FACTOR Coefficient de friction $2 g d_{50} S / V^2$
			d 50 pc		d 10 pc			V (ft/sec)	S		
			(mm)	(ft)	(mm)	(ft)					
1	BM3 2 3/4" Blue Metal Doléríte	45.5	11	3.6×10^{-2}	16	5.2×10^{-2}	1.25 + 0.17 — 0.02	0.805 9.8×10^{-2} 3.31×10^{-2} 1.12×10^{-2} 1.8×10^{-3} 5.4×10^{-4}	10.0 0.194 2.96×10^{-2} 5.45×10^{-3} 5.2×10^{-4} 1.6×10^{-4}	3.35×10^3 4.07×10^2 1.38×10^2 4.66×10^1 7.5 2.25	5.17×10^1 6.77×10^1 9.01×10^1 1.46×10^2 5.38×10^2 1.84×10^3
2	M1 23 Marble Mixture Billes mélangées	37.9	15.8	5.2×10^{-2}	24.9	8.2×10^{-2}	1.34 + 0.03 — 0.05	1.25 0.138 2.61×10^{-2} 9.9×10^{-3} 7.0×10^{-4}	11.5 0.188 1.00×10^{-2} 2.19×10^{-3} 1.48×10^{-4}	7.65×10^3 8.45×10^2 1.60×10^2 6.06×10^1 4.28	3.89×10^1 5.22×10^1 7.75×10^1 1.18×10^2 1.59×10^3
4	G1 Nepean Sand Sable	38.7	0.27	8.9×10^{-4}	0.53	1.74×10^{-3}	1.42 + 0.03 — 0.02	4.50×10^{-2} 1.50×10^{-2} 6.1×10^{-5} 2.0×10^{-6}	11.5 3.13 1.28×10^{-2} 6.2×10^{-4}	5.51 1.84 7.47×10^{-3} 2.45×10^{-4}	6.35×10^2 1.56×10^3 3.86×10^5 1.74×10^7
5	G3 3/8" River Gravel Grav. de riv.	39.2	2.0	6.6×10^{-3}	5.8	1.9×10^{-2}	1.42 + 0.01 — 0.02	0.209 4.35×10^{-2} 1.12×10^{-2} 3.27×10^{-3} 1.74×10^{-4}	10.0 0.675 8.95×10^{-2} 1.95×10^{-2} 1.00×10^{-3}	2.80×10^2 5.82×10^1 1.50×10^1 4.38 2.33×10^{-1}	2.80×10^2 4.37×10^2 8.77×10^2 2.23×10^3 4.03×10^4
6	G2 1/4" River Gravel Grav. de riv.	41.8	0.95	3.1×10^{-3}	2.3	7.5×10^{-3}	1.40 + 0.01 — 0.00	0.200 0.141 4.60×10^{-2} 7.5×10^{-3} 1.30×10^{-4} 6.0×10^{-6}	13.4 7.37 1.44 0.160 2.78×10^{-3} 1.97×10^{-4}	1.07×10^2 7.55×10^1 2.46×10^1 4.02 6.96×10^{-2} 3.21×10^{-3}	1.62×10^2 1.79×10^2 3.28×10^2 1.37×10^3 7.95×10^4 2.65×10^6
8	BM1 3/16" Blue Metal Doléríte	47.7	1.9	6.2×10^{-3}	3.2	1.05×10^{-2}	1.41 + 0.03 — 0.01	0.350 2.91×10^{-2} 4.6×10^{-3} 1.54×10^{-3} 4.5×10^{-5}	12.7 0.179 1.96×10^{-2} 6.45×10^{-3} 3.9×10^{-4}	2.61×10^2 2.17×10^1 3.43 1.15 3.35×10^{-2}	6.98×10^1 1.43×10^2 6.25×10^2 1.84×10^3 1.30×10^5
9	BM2 3/8" Blue Metal Doléríte	45.8	4.7	1.54×10^{-2}	6.4	2.10×10^{-2}	1.41 + 0.02 — 0.04	0.463 3.90×10^{-2} 6.70×10^{-3} 1.04×10^{-3} 9.0×10^{-5}	12.5 0.170 1.40×10^{-2} 2.20×10^{-3} 3.07×10^{-4}	6.90×10^2 5.81×10^1 9.98 1.55 1.34×10^{-1}	7.90×10^1 1.51×10^2 4.21×10^2 2.76×10^3 5.12×10^4
10	G6 3" River Gravel Grav. de rivière	36.9	40	1.31×10^{-1}	55	1.80×10^{-1}	1.37 + 0.04 — 0.04	1.02 3.27×10^{-2} 9.0×10^{-3}	5.04 8.0×10^{-3} 9.0×10^{-4}	1.34×10^4 4.30×10^2 1.18×10^2	5.62×10^1 8.67×10^1 1.29×10^2
11	BM5 3" Blue Metal Doléríte	48.3	25	8.2×10^{-2}	37	1.21×10^{-1}	1.39 + 0.04 — 0.04	0.94 3.59×10^{-2} 7.5×10^{-3} 1.7×10^{-3}	10.0 2.00×10^{-2} 1.2×10^{-3} 1.6×10^{-4}	8.18×10^3 3.13×10^2 6.53×10^1 1.48×10^1	8.82×10^1 1.21×10^2 1.66×10^2 4.32×10^2
12	G5 1 1/2" River Gravel Grav. de riv.	37.2	19	6.2×10^{-2}	26	8.5×10^{-2}	1.40 + 0.00 — 0.00	0.855 5.9×10^{-2} 6.1×10^{-3} 1.4×10^{-3}	10.0 7.17×10^{-2} 1.64×10^{-3} 2.38×10^{-4}	5.19×10^3 3.58×10^2 3.70×10^1 8.5	7.49×10^1 1.13×10^2 2.41×10^2 6.65×10^2

Tableau 2

Nombres de Reynolds limitants et coefficients de frottement correspondant aux divers régimes d'écoulement

TEST SERIES Série d'essais n°	MATERIAL Matériau	PORO- SITY Porosité P (pc)	CHARACTERISTIC PARTICLE LENGTHS Longueurs caractéristiques des grains				WATER KINEMATIC VISCOSITY Viscosité ciné- matique de l'eau $\nu \times 10^5$ (ft²/sec)	CRITICAL VALUES FROM EXPERIMENTAL GRAPHS Valeurs critiques tirées des courbes expérimentales		REYNOLDS NUMBER Nombre de Reynolds Vd_{50}/ν	FRICTION FACTOR Coefficient de friction $2gd_{50}S/V^2$
			d 10 pc		d 50 pc			V (ft/sec)	S		
			(mm)	(ft)	(mm)	(ft)					
13	G4 3/4" River Gravel Grav. de riv.	36.7	12	3.9×10^{-2} $d_{10}/d_{50} =$	16	5.2×10^{-2} 0.75	1.40 + 0.017 — 0.001	0.63 4.6×10^{-2} 1.36×10^{-2} 5.35×10^{-3} 1.2×10^{-3}	10.0 9.0×10^{-2} 1.30×10^{-2} 3.30×10^{-3} 4.83×10^{-4}	2.34×10^3 1.71×10^2 5.05×10^1 1.99×10^1 4.46	8.43×10^1 1.42×10^2 2.35×10^2 3.86×10^2 1.12×10^3
14	BM4 1 1/2" Blue Metal Dolérite	43.8	19	6.2×10^{-2} $d_{10}/d_{50} =$	25	8.2×10^{-2} 0.76	1.41 + 0.02 — 0.01	0.95 7.1×10^{-2} 1.23×10^{-2} 5.0×10^{-3}	10.0 7.5×10^{-2} 3.5×10^{-3} 9.3×10^{-4}	5.52×10^3 4.13×10^2 7.15×10^1 2.91×10^1	5.85×10^1 7.85×10^1 1.22×10^2 1.96×10^2
15	BM3 1 3/4" Blue Metal Dolérite	42.8	10.5	3.4×10^{-2} $d_{10}/d_{50} =$	14	4.6×10^{-2} 0.75	1.39 + 0.02 — 0.03	0.69 4.10×10^{-2} 4.4×10^{-3} 1.2×10^{-3}	10.0 5.85×10^{-2} 2.14×10^{-3} 4.27×10^{-4}	2.28×10^3 1.36×10^2 1.46×10^1 3.97	6.22×10^1 1.03×10^2 3.26×10^2 8.80×10^2
16	M1 16 mm Marbles Billes	36.9	15.6	5.11×10^{-2} $d_{10}/d_{50} =$	16.0	5.24×10^{-2} 0.98	1.38 + 0.02 — 0.03	0.895 9.4×10^{-2} 2.80×10^{-2} 5.17×10^{-3} 8.0×10^{-4}	8.0 0.131 1.72×10^{-2} 1.53×10^{-3} 2.33×10^{-4}	3.40×10^3 3.57×10^2 1.06×10^2 1.96×10^1 3.04	3.38×10^1 5.01×10^1 7.41×10^1 1.94×10^2 1.23×10^3
17	M2 25 mm Marbles Billes	36.9	24.6	8.06×10^{-2} $d_{10}/d_{50} =$	24.9	8.16×10^{-2} 0.99	1.37 + 0.03 — 0.02	1.06 0.180 3.92×10^{-2} 1.00×10^{-3}	7.00 0.255 1.69×10^{-2} 5.4×10^{-5}	6.31×10^3 1.07×10^3 2.34×10^2 5.95	3.28×10^1 4.13×10^1 5.77×10^1 2.84×10^2
18	G7 6" River Gravel Grav. de rivière	40.6	84	2.75×10^{-1} $d_{10}/d_{50} =$	110	3.60×10^{-1} 0.76	1.37 + 0.03 — 0.05	1.35 7.0×10^{-2} 5.85×10^{-3}	2.50 8.8×10^{-3} 1.00×10^{-4}	3.55×10^4 1.84×10^3 1.54×10^2	3.19×10^1 4.16×10^1 6.78×10^1
19	M1 16 mm Marbles Billes	41.5	15.6	5.11×10^{-2} $d_{10}/d_{50} =$	16.0	5.24×10^{-2} 0.98	1.30 + 0.05 — 0.07	0.510 0.172 1.72×10^{-2} 7.7×10^{-3} 1.16×10^{-3}	1.60 0.215 4.00×10^{-3} 1.29×10^{-3} 1.8×10^{-4}	2.06×10^3 6.94×10^2 6.94×10^1 3.11×10^1 4.68	2.08×10^1 2.46×10^1 4.57×10^1 7.33×10^1 4.50×10^2
20	M1 16 mm Marbles Billes	37.2	15.6	5.11×10^{-2} $d_{10}/d_{50} =$		5.24×10^{-2} 	1.24 + 0.00 — 0.00	0.450 9.1×10^{-2} 1.80×10^{-2} 6.5×10^{-3}	1.88 0.104 6.5×10^{-3} 1.52×10^{-3}	1.90×10^3 3.85×10^2 7.60×10^1 2.75×10^1	3.13×10^1 4.25×10^1 6.78×10^1 1.21×10^2
21	BM3 1 3/4" Blue Metal Dolérite	51.5	10.5	3.4×10^{-2} $d_{10}/d_{50} =$	14	4.6×10^{-2} 0.75	1.23 + 0.00 — 0.01	0.400 8.0×10^{-2} 2.33×10^{-2} 5.2×10^{-3} 2.00×10^{-3}	1.50 7.2×10^{-2} 8.8×10^{-3} 1.00×10^{-3} 3.05×10^{-4}	1.50×10^3 2.99×10^2 8.71×10^1 1.95×10^1 7.48	2.78×10^1 3.33×10^1 4.80×10^1 1.10×10^2 2.26×10^2
22	M3 29 mm Marbles Billes	38.5	28.5	9.35×10^{-2} $d_{10}/d_{50} =$	29.0	9.5×10^{-2} 0.98	1.20 + 0.04 — 0.02	1.13 5.80×10^{-2} 3.90×10^{-3}	6.00 2.45×10^{-2} 3.30×10^{-4}	8.95×10^3 4.59×10^2 3.09×10^1	2.87×10^1 4.46×10^1 1.33×10^2

Inspection of the results in Table 1 is sufficient to reveal the lack of correlation.

Two correlations, however, gave better results.

The first, between the value of a for the pre-linear regime and a for the linear regime, is shown in Figure 10. With only four points available for the graph, it is possible that the correlation is only accidental.

The second, shown in Figure 11, between the hydraulic gradient for the upper limit of the linear regime and the value of a for this regime (i.e. the reciprocal of coefficient of permeability) is interesting. It appears that the use of this correlation graph would allow more accurate predictions of the upper limit of flow conditions for which Darcy's law is valid than predictions based on Reynolds number. An unfortunate feature of the use of a correlation between limiting hydraulic gradient and permeability is that permeability must be determined by experiment if a reasonable estimate is to be made. In many cases it would then be simpler to determine the limiting hydraulic gradient experimentally.

7. Conclusions

(a) The results of this investigation show that the form of the velocity-hydraulic gradient relationship for the flow of water through coarse granular media is a discontinuous exponential one of the form

$$S = aV^n$$

A number of flow regimes occur, each with its own value of a and n . Abrupt changes of a and n separate the regimes.

The regimes which may occur for a particular medium can be classified into :

- (i) A linear regime for which n equals 1. In this regime Darcy's law is valid;
- (ii) A pre-linear regime for which n is less than 1. In this regime non-Newtonian characteristics caused by interfacial tension or the association of water molecules may be attributed to the water;
- (iii) Several post-linear regimes for which n is greater than 1.

(b) The results could not be generalised in terms of friction factor and Reynolds number because the media tested were not geometrically similar.

In the absence of generally applicable friction factor-Reynolds number plots there is little advantage to be gained by expressing the results of permeability tests in this form.

(c) Predictions of the upper limit of validity of Darcy's law based on a limiting hydraulic gradient-permeability correlation appear to be more accurate than those based on a limiting Reynolds number. However, additional information beyond that required to calculate Reynolds number is required.

(d) A correlation between the values of a for the pre-linear regime and a (and thus coefficient of permeability, k) for the linear regime may exist.

List of symbols

- a, b, c : equation constants;
 d : median particle diameter;
 f : Darcy's friction factor;
 f_D : Bakhmeteff's modified friction factor;
 g : gravitational acceleration;
 n : equation exponent;
 A : gross cross-sectional area of flow;
 P : porosity;
 Q : discharge or volume flow rate;
 $\mathcal{R}$: Reynolds number;
 $\mathcal{R}_D$: Bakhmeteff's modified Reynolds number;
 S : hydraulic gradient;
 S_p : pressure gradient;
 V : velocity = (Q/A) ;
 γ : specific weight of fluid;
 ν : kinematic viscosity of fluid.

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Résumé

Etude expérimentale de l'écoulement de l'eau par des milieux à gros grains par C. R. Dudgeon *

L'équation classique, définissant la relation entre le débit et le gradient hydraulique, de l'écoulement de l'eau en régime « laminaire » par un milieu poreux, correspond à la loi de Darcy, et peut s'écrire $S = aV$, avec S : gradient hydraulique; V : vitesse d'écoulement, soit : débit/section globale; a : l'inverse du coefficient de perméabilité k .

Des écarts par rapport à cette loi, constatés aux débits élevés, ont été attribués à des efforts d'inertie, et à l'apparition de la turbulence. Les limites supérieures constatées pour cette loi, et exprimées pour la plupart en fonction du nombre de Reynolds, varient fortement.

Pour les débits élevés, les équations proposées le plus souvent sont :

$$S = aV + bV^2 \text{ et } S = aV^n, a, b, n, \text{ étant des Ctes.}$$

La validité de la loi de Darcy a également été mise en doute dans la gamme des très faibles débits, et principalement pour le cas des matériaux argileux constitués de grains très fins. Les écarts constatés ont été attribués à une interaction « électro-chimique » aux interfaces liquide/solide.

L'étude expérimentale présentée était conçue de manière à tenir compte de la gamme de régimes d'écoulement le plus étendue possible, en vue de mieux définir la nature de la relation liant la vitesse au gradient hydraulique.

Des essais de perméabilité ont été effectués avec des billes de verre, de la dolérite broyée, et des graviers de rivière, dont les diamètres médians étaient compris entre 0,5 et 110 mm. Les billes étaient de forme sphérique, les graviers de rivière étaient bien arrondis et, pour la plupart, constitués de roche ignée ou métamorphique, ou de quartz, et les fragments de dolérite broyée étaient angulaires et rugueux.

Un perméamètre spécial, conçu de manière à éliminer les phénomènes dus à l'influence des parois, a été employé pour ces essais. Cet appareil était du type à écoulement du haut en bas, avec un diamètre intérieur de 57 cm, et une longueur d'échantillon de 76 ou 102 cm. Les pertes de charge ont été mesurées sur des longueurs de 51 ou 76 cm.

La section d'écoulement à la sortie comportait un tube collecteur intérieur, ayant pour objet de séparer l'écoulement d'eau descendant à l'intérieur d'une zone intérieure de 35,6 cm de diamètre, de l'écoulement entre cette zone et la paroi extérieure. Les charges ont été maintenues à une valeur constante sur toute la largeur du pied de l'échantillon, par réglage « ad hoc » des pertes de charge des tuyaux d'écoulement à la sortie.

Un soin tout particulier a été apporté à la mesure précise des débits et des pertes de charge correspondant à des gradients hydrauliques variant d'environ 10 à 10^{-4} , et pour des vitesses variant d'environ 40 cm/s à 6.10^{-5} cm/s. L'eau employée pour ces essais provenait d'un barrage situé dans un bassin versant essentiellement gréseux, et ne contenait qu'une faible quantité de matières chimiques. Aucun dégazage de cette eau n'a été effectué, compte tenu de ce que les expériences ont porté uniquement sur des matériaux grossiers.

Avant de recueillir des résultats, on a stabilisé l'échantillon en y faisant passer de l'eau, au débit maximal, pendant quelque temps. Les valeurs des porosités ont été calculées à partir du poids du matériau présent dans le perméamètre, de sa densité, et du volume qu'il occupait à la fin des expériences. Elle ont été vérifiées en mesurant le volume d'eau écoulé du perméamètre, entre deux niveaux piézométriques, et en tenant compte, de manière adéquate, de l'eau retenue sur la surface des grains.

Les résultats obtenus ont montré que, pour les matériaux étudiés et compte tenu de gradients hydrauliques variables de 10^{-4} à 10 , la relation liant la vitesse au gradient hydraulique était exponentielle et discontinue, de la forme $S = aV^n$.

On a constaté l'existence de plusieurs régimes d'écoulement dans tous les cas, dont chacun correspondait à une droite en coordonnées à double échelle logarithmique. Les différents régimes étaient séparés par des discontinuités brusques en ce qui concerne le domaine pratique.

En employant la notation de Slepíčka (3), il était possible de classer ces régimes, et de distinguer entre des régimes linéaire, post-linéaire, et pré-linéaire, correspondant respectivement à : $n = 1$, $n > 1$ et $n < 1$.

Des mesures effectuées à l'aide d'une sonde piézo-électrique très sensible, en vue de situer l'apparition de la turbulence, n'ont pas abouti à des conclusions définitives. Il est probable que les résultats obtenus ne reflétaient que des phénomènes perturbés, et localisés au voisinage immédiat de la sonde, et non des régimes moyens et non-perturbés, présents dans l'ensemble des échantillons.

La représentation graphique des résultats des essais de perméabilité, en portant le coefficient de frottement en fonction du nombre de Reynolds, ont montré qu'il n'était guère possible de déduire une équation générale pour tenir compte de cette relation. Il semble que l'influence complexe de la porosité, des dimensions et des formes des grains, et de la répartition granulométrique sur la similitude géométrique des milieux poreux, rende ce problème analogue à celui de la recherche d'une courbe unique, représentant la variation du coefficient de frottement en fonction du nombre de Reynolds, pour tous les tuyaux, quelles qu'en soient la forme et les dimensions, et quels qu'en soient les profils de rugosité, les dimensions, et la répartition des protubérances rugueuses.

Puisque l'on ne dispose d'aucune courbe généralisée tenant compte de la variation du coefficient de frottement en fonction du nombre de Reynolds, il paraît logique de continuer à présenter les résultats des essais de perméabilité en fonction de la vitesse d'écoulement, et du gradient hydraulique.

On a essayé d'établir des corrélations entre certaines propriétés des courbes de la vitesse en fonction du gradient hydraulique. Il s'est montré que la définition de la limite supérieure du régime linéaire (de Darcy) pouvait se faire plus aisément à partir d'une corrélation avec le coefficient a (ou bien avec le coefficient de perméabilité) que sur la base d'une corrélation avec le nombre de Reynolds. Cependant, l'emploi d'une telle corrélation suppose que l'on disposerait de données complémentaires, par rapport à celles nécessaires pour le calcul du nombre de Reynolds.

Il paraissait exister une corrélation entre la valeur du coefficient a , correspondant au régime pré-linéaire, et la valeur de ce même coefficient pour le régime linéaire, mais on ne disposait que de quatre points.

Il paraissait également, qu'à l'intérieur du perméamètre, l'influence des parois était telle que la vitesse moyenne, par l'ensemble de la section transversale de l'échantillon, dépassait celle par la zone intérieure. Pour les matériaux étudiés, cet excès de vitesse variait de 5 % à 15 %. Des études complémentaires sur l'influence des parois sont actuellement en cours.

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